

Superflares from magnetars revealing the GRB central engine

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ABSTRACT

Long-duration gamma-ray bursts (GRBs) may be powered by the rotational energy of a millisecond magnetar. I argue that the GRB-driving magnetars lie at the high end of the distribution of magnetic field strengths of magnetars. The field of GRB magnetars decays on timescale of hundreds of years and can power SGR-like flares up to ~ 100 times more powerful than the 2004 event of SGR 1806–20. A few of these flares per year may have been observed by *BATSE* and classified as short-duration GRBs. Association of one of these superflares with a nearby $d_L \lesssim 250$ Mpc galaxy and the discovery of a, coincident in space, 100-year-old GRB afterglow (observed in the radio) will be the characteristic signature of the magnetar model for GRBs.

Key words: Gamma rays: bursts – magnetic fields – stars: neutron

1 INTRODUCTION

While long-duration GRBs have been shown to be associated with core-collapse supernovae (Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003), the details on how the central engine of GRBs operates remain elusive. The core of the star may collapse into a few solar mass black hole accretion into which powers the GRB flow (Woosley 1993). Alternatively, a millisecond period proto-magnetar may form at the stellar core. In this model, magnetic fields extract the rotational energy of the magnetar launching the GRB flow (Usov 1992; Thompson 1994).

Magnetars born with dipole surface fields $B_s \sim 10^{14} - 10^{15}$ G are common making up around $\sim 10\%$ of the neutron star population with a Galactic birth rate of $\sim 10^{-3} \text{ yr}^{-1}$ (Kouveliotou et al. 1998). This rate is 2–3 orders of magnitude higher than that of long-duration GRBs (corrected for beaming; Guetta, Piran and Waxman 2005). If GRBs are connected to magnetar birth, a very small fraction of magnetars power GRBs indicating that special conditions need to be satisfied.

From the theoretical perspective, fast rotation and very strong fields (even in comparison to those inferred for the Galactic magnetars) appear to be needed for a successful magnetar model for GRBs (Thompson, Chang and Quataert 2004; Uzdensky and MacFadyen 2007; Metzger, Thompson and Quataert 2007; Bucciantini et al. 2009; see also Kluźniak and Ruderman 1998; Spruit 1999). Metzger et al. (2007) explored a variety of models for the proto-neutron star wind finding that $B \gtrsim 3 \times 10^{15}$ G and $P \simeq 1$ ms are required for a powerful wind of low baryon loading to be launched within tens of seconds as needed to explain GRBs.

Galactic magnetars can release a substantial fraction of their

magnetic energy during powerful flares. The supergiant flare of the soft gamma-ray repeater (SGR) 1806–20 resulted in the release of $E_f \sim 10^{46}$ ergs on a time scale of ~ 0.2 s (Palmer et al. 2005; Hurley et al. 2005; Frederiks et al. 2007; for a review see Mereghetti 2008). This energy corresponds to a fraction $\sim 0.1 R_6^{-3} B_{15}^{-2}$ of the total magnetic energy contained in the neutron star, where $R = 10^6 R_6$ cm is the radius of the star and $B = 10^{15} B_{15}$ G is the interior field strength. Such a flare could be detected up to a distance of tens of Mpc by *BATSE* (Palmer et al. 2005, Hurley et al. 2005).

Here, I argue that SGR flares from GRB-driving magnetars are a factor of ~ 100 brighter than the December 2004 flare of SGR 1806–20 because of their tenfold stronger fields. Such flares should take place \sim hundreds of years after the formation of the magnetar (and the associated GRB) and can be observed out to distance of ~ 250 Mpc. I estimate that a few of these flares should be observed per year. Radio observations at the location of the flare may be able to detect and resolve the GRB afterglow proving the magnetar-GRB association.

2 SUPERFLARES FROM GRB-DRIVING MAGNETARS

The December 27, 2004 flare from SGR 1806–20 was extremely intense on Earth. Saturation of the instruments makes the peak flux and spectrum of the flare hard to determine. Estimates for the peak luminosity of the flare range at $L_f \sim 0.7 \div 1.7 \times 10^{47}$ ergs/s with the energy contained in the spike being $E_f \sim 0.5 \div 1.7 \times 10^{46}$ ergs (assuming isotropic explosion and the revised distance of $d \simeq 9$ kpc found in Bibby et al. 2008). The spectrum during the flare is described by a power-law followed by an exponential cutoff slightly below ~ 1 MeV (Palmer et al. 2005; Frederiks et al. 2007).

SGR 1806–20 has estimated surface magnetic field of $B_s \sim$

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8×10^{14} G within the typical range of the other known magnetars (Kouveliotou et al. 1998). For an interior magnetic field of $B \sim 10^{15}$ G, the total magnetic energy contained in the star (decay of which is believed to power the SGR activity) is

$$E_B = R^3 B^2 / 6 = 1.6 \times 10^{47} R_6^3 B_{15}^2 \text{ erg.} \quad (1)$$

Since the observed energy of the flare is not orders of magnitude less than E_B , a substantial fraction (say 10%) of the magnetic energy of the magnetar can be released in a single event.

The SGR and Anomalous X-ray Pulsar (AXP) activity in Galactic magnetars lasts for $\sim 10^4$ years and is believed to be connected to the time it takes for the magnetic field of the neutron star to decay. For magnetic fields in the magnetar range, the field decay is mostly connected to ambipolar diffusion leading to (Thompson and Duncan 1996; Heyl and Kulkarni 1998)

$$t_{\text{dec}} \sim 10^4 / B_{15}^2 \text{ yr,} \quad (2)$$

that can be complicated by the cooling history of the neutron star (not appearing explicitly in the last expression).

Successful models of magnetars as central engines for GRBs consider core collapse to millisecond protomagnetars of $B \gtrsim 3 \times 10^{15}$ G (Metzger et al. 2007) with interior fields reaching strengths as high as $B \sim 10^{17}$ G for substantial differential rotation of the protoneutron star (Kluźniak and Ruderman 1998; Spruit 1999)¹. Under these conditions ~ 10 s after core collapse the proto magnetar cools enough for its neutrino-driven wind to weaken and a high- σ GRB jet to be launched (Usov 1992; Thompson et al. 2004; Metzger et al. 2007). Assuming that the protoneutron star does not collapse into a black hole shortly after the GRB, we are left with a magnetar of interior field of $B \sim 10^{16}$ G. This field is expected diffuse from the magnetar on timescale of $\sim 100 \div 1000$ yr (Heyl and Kulkarni 1998; ; Dall’Osso, Shore and Stella 2009; that is much shorter of the typical Galactic magnetar lifetime) possibly powering SGR-type flares. Because of the stronger magnetic field at birth with respect to that of a Galactic magnetar, the flares from GRB-driving magnetars can be some 2 orders of magnitude more powerful than the August 2004 flare of SGR 1806–20. The energy released in such “superflares” can be $E_{\text{sf}} \sim 0.1 E_B \sim 10^{48} R_6^3 B_{16}^2$ erg. Assuming duration of the superflares of ~ 0.1 s, their peak luminosity is $L_{\text{sf}} \sim 10^{49}$ ergs/s.² Since not all the energy is used up in a single flaring a number of f repetitions from the same source where $f \sim$ a few is also possible.

3 PREDICTED RATES OF SUPERFLARES

The distance out to which a flare from a GRB magnetar can be observed depends on both luminosity and spectrum. Assuming that the bulk of the energy of the flare is emitted at around ~ 1 MeV (as in the 2004 flare of SGR 1806–20), *BATSE* could detect such flare at a luminosity distance of $d_L \approx 250 L_{49}^{1/2}$ Mpc (e.g. Popov & Stern 2006). Guetta et al. (2005) estimate the local ($z = 0$) rate

¹ The fast rotation and very strong fields are likely connected since the $P \approx 1$ ms rotation can lead to powerful magnetic fields through an efficient α – Ω dynamo (Duncan and Thompson 1992; Thompson and Duncan 1993).

² If the duration of the SGR flares is connected to the time it takes for Alfvén waves to cross the neutron star (Thompson and Duncan 1996), the duration of the superflare can be shorter than 0.1 s increasing its peak luminosity (for the same total energy released) and, therefore, detectability. Such flares will fall within the short range of the duration distribution of short GRBs.

per unit volume of long-duration GRBs (corrected for beaming) to be $R_{\text{GRB}} \sim 43 H_{71}^3 \text{ Gpc}^{-3} \text{ yr}^{-1}$, where $H_0 = 71 H_{71} \text{ km/s/Mpc}$ is the Hubble constant. If every long GRB leaves a magnetar behind that powers f superflares, the rate of superflares within d_L is³

$$\dot{R}_{\text{sf}} = 4\pi d_L^3 R_{\text{GRB}} f / 3 = 2.8 f L_{49}^{3/2} \text{ yr}^{-1}. \quad (3)$$

This estimate shows that a few tens of the *BATSE* triggers over the 9 years of the mission can be relatively nearby superflares. These superflares would be classified as short GRBs. Out of the ~ 700 short-duration GRBs observed by *BATSE* a fraction of $\sim 0.036 f L_{49}^{3/2}$ may be flares from GRB-related magnetars.

The 2004 December 27 flare from SGR 1806–20 would have been visible by *BATSE* out to tens of Mpc (Hurley et al. 2005; Palmer et al. 2005). This triggered several studies on the possibility that a fraction of short GRBs consists of SGR flares *similar* to that of SGR 1806–20 (Lazzati, Ghirlanda and Ghisellini 2005; Tanvir et al. 2005; Popov and Stern 2006; Nakar et al. 2006; Chapman, Priddey and Tanvir 2009). Upper limits on this fraction of the order of $\sim 10\%$ were found by the lack of definite short GRB detections consistent with the Virgo cluster (Palmer et al. 2005; Popov and Stern 2006), lack of possible hosts within 100 Mpc for six well localized GRBs (Nakar et al. 2006), and the comparison with spectra of the brightest *BATSE* short GRBs (Lazzati et al. 2005; hereafter L05). While these studies put constraints on the fraction of Short GRBs originating within tens of Mpc, they cannot constrain the possible contribution of superflares from GRB-related magnetars (discussed in this paper) to the *BATSE* sample. Superflares are more rare, luminous and can be detected out to \sim hundreds of Mpc.⁴ Interestingly, Tanvir et al. (2005) and Chapman et al. (2009) find that some $\sim 20\%$ of the *BATSE* short GRBs with localization better than 10° are correlated with galaxies out to ~ 150 Mpc. A fraction of these bursts may come from GRB-magnetar flares.

4 A MAGNETAR FLARE REVEALING AN OLD GRB AFTERGLOW

Although an estimated a few long-duration GRBs per year take place within ~ 250 Mpc (using the rates of, e.g., Guetta et al. 2005), we miss the prompt and early afterglow emissions from $\sim 99\%$ of them because they are beamed away from us. About ten years after the GRB, however, the blast wave has decelerated to sub-relativistic speeds and the afterglow emission is bright at all directions. The magnetar flares can point to the location where a long GRB *has already taken place some ~ 100 – 1000 years ago* (the time it takes for

³ This estimate assumes that the superflares are isotropic. If the flares are beamed within a solid angle $\delta\Omega_{\text{sf}} < 4\pi$, only a fraction $\delta\Omega_{\text{sf}}/4\pi$ of the flares will be observed. On the other hand, each flare will consume a factor $\delta\Omega_{\text{sf}}/4\pi$ less magnetic energy from the magnetar potentially allowing for a larger number of flares to occur. In this case f stands for the number of flares emitting within the observer’s line of sight.

⁴ L05 argue that no more than $\sim 4\%$ of the *BATSE* short bursts are SGR flares, the reason being that only few short GRBs are described by a thermal spectrum that was inferred for the 2004 SGR 1806–20 flare (Boggs et al. 2007). However, the spectrum from the flare of SGR 1806–20 was hard to measure because of saturation of the detectors and may actually be non-thermal (Palmer et al. 2005; Frederiks et al. 2007) making the L05 analysis less constraining. In any case our estimate on the superflares “hidden” in the short GRB sample is rather comparable to the 4% upper limit found by L05.

$B \sim 10^{16}$ G fields to decay)⁵. Here, I show that the GRB afterglow emission should be still detectable in the radio when the superflare takes place.

GRB afterglows can be followed in the radio wavelengths for years after the burst. GRB 030329 is an intrinsically typical long GRB that took place particularly nearby at $z = 0.1685$ (or luminosity distance of $d_L = 800$ Mpc for standard cosmology; Greiner et al. 2003). Its radio afterglow remains fairly bright (at the mJy level) years after the burst and the blastwave is resolved (e.g. Berger et al. 2003; Taylor et al. 2004; Resmi et al. 2005; Frail et al. 2005; Pihlström et al. 2007; van der Horst et al. 2008). Because of the slow decline in flux, the afterglow is expected to be observable over the next decade in the GHz range and be resolved ~ 7 years after the burst (Pihlström et al. 2007). With the Low Frequency Array (LOFAR) the afterglow of GRB 030329 can be detected for several decades (van der Horst et al. 2008).

The afterglow emission of a GRB similar to that of 030329 located at a distance $d_L \sim 250$ Mpc will be ~ 10 times more bright and with the radio image a factor of ~ 2.6 larger. Such an afterglow emission can be detected and resolved for hundred (or hundreds) of years after the burst. Two-dimensional relativistic hydrodynamical simulations (Zhang and MacFadyen 2009) indicate that the GRB blast reaches a distance of ~ 3 pc at ~ 100 years which corresponds to a source of angular size of ~ 2.7 mas (for a corresponding angular distance of $d_A \sim 224$ Mpc) and flux density of ~ 0.1 mJy (at ~ 1 GHz) allowing for the morphological study of the blastwave with high-sensitivity Very Long Baseline Interferometry (VLBI) observations similar to those reported in Pihlström et al. (2007). According to the same simulations, the decelerating GRB blastwave is morphologically very different from a supernova remnant for the first ~ 200 years allowing for the distinction between the two types of explosions.

For radio follow-ups to be possible, a good enough localization of the superflare is needed. Such localization can be provided with the Burst Alert Telescope (BAT) detector on *SWIFT*. The rate at which *SWIFT* detects GRBs is $\sim 1/3$ of that of *BATSE* mainly because of its smaller field of view. I, thus, estimate that *BAT* detects $\dot{R}_{\text{sf}}/3 \sim 1 f L_{49}^{3/2}$ superflares per year. *FERMI* detection rate of flares is a factor of ~ 2.5 higher but the Glasp Burst Monitor (*GBM*) lacks the localization needed for a radio follow-up. The pulsating tail that is expected to follow the superflare may, in some cases, be powerful enough to be observed with *XRT* hundreds of seconds after the event. Although the pulsating tails that follow bright SGR flares of Galactic magnetars for $\sim 200 - 400$ s have $L_{\text{tail}} \sim 10^{42}$ ergs/s (Mereghetti 2008), the strong magnetic field of the GRB magnetar can confine ~ 100 times more energy in the magnetosphere of the neutron star resulting in far brighter X-ray tails. It is furthermore possible that the superflare has a strong enough “afterglow” of its own that allows for X-ray (or longer wavelength) detection and accurate localization shortly after the burst (Eichler 2002).

5 SUMMARY

If GRB-magnetars exist, their magnetic field should decay on a time-scale of a few hundred years possibly producing SGR-like flares with peak luminosities of $\sim 10^{49}$ ergs/s. A few of these flares

per year should have been detected by *BATSE* out to $d_L \sim 250$ Mpc classified as short-duration GRBs. Such superflares can be detected with *SWIFT* at a rate of about one per year. The host galaxy of the flare should be typical of those of long-duration GRBs. High sensitivity radio observations at the location of the flare can resolve a ~ 100 -year-old blastwave result of the interaction of the GRB jets with the circumburst medium. This detection can prove that GRBs are connected to the birth of magnetars.

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REFERENCES

- Berger E. et al., 2003, *Nature*, 426, 154
- Bibby J. L., Crowther P. A., Furness J. P., Clark J. S., 2008, *MNRAS*, 386, L23
- Boggs S. E., Zoglauer A., Bellm E., Hurley K., Lin R. P., Smith D. M., Wigger C., Hajdas W., 2007, *ApJ*, 661, 458
- Bucciantini N., Quataert E., Metzger B. D., Thompson T. A., Arons J., Del Zanna L., 2009, *MNRAS*, 396, 2038
- Chapman R., Priddey R. S., Tanvir N. R., 2009, *MNRAS*, 395, 1515
- Dall’Osso S., Shore S. N., Stella L., 2009, *MNRAS*, 398, 1869
- Duncan R. C., Thompson C., 1992, *ApJ*, 392, L9
- Eichler D., 2002, *MNRAS*, 335, 883
- Frail D. A., Soderberg A. M., Kulkarni S. R., Berger E., Yost S., Fox D. W., Harrison F. A., 2005, *ApJ*, 619, 994
- Frederiks D. D., Golenetskii S. V., Palshin V. D., Aptekar R. L., Ilyinskii V. N., Oleinik F. P., Mazets E. P., Cline T. L., 2007, *Astronomy Letters*, 33, 1
- Galama T. J. et al., 1998, *Nature*, 395, 670
- Greiner J., Peimbert M., Estaban C., Kaufer A., Jaunsen A., Smoke J., Klose S., Reimer O., 2003, *GRB Coordinates Network*, 2020, 1
- Guetta D., Piran T., Waxman E., 2005, *ApJ*, 619, 412
- Heyl J. S., Kulkarni S. R., 1998, *ApJ*, 506, L61
- Hjorth J. et al., 2003, *Nature*, 423, 847
- Hurley K. et al., 2005, *Nature*, 434, 1098
- Kluźniak W., Ruderman M., 1998, *ApJ*, 505, L113
- Kouveliotou C. et al., 1998, *Nature*, 393, 235
- Lazzati D., Ghirlanda G., Ghisellini G., 2005, *MNRAS*, 362, L8
- Mazzali P. A. et al., 2003, *ApJ*, 599, L95
- Mereghetti S., 2008, *A&ARv*, 15, 225
- Metzger B. D., Thompson T. A., Quataert E., 2007, *ApJ*, 659, 561
- Nakar E., Gal-Yam A., Piran T., Fox D. B., 2006, *ApJ*, 640, 849
- Palmer D. M. et al., 2005, *Nature*, 434, 1107
- Pihlström Y. M., Taylor G. B., Granot J., Doeleman S., 2007, *ApJ*, 664, 411
- Popov S. B., Stern B. E., 2006, *MNRAS*, 365, 885
- Resmi L. et al., 2005, *A&A*, 440, 477
- Spruit H. C., 1999, *A&A*, 341, L1
- Stanek K. Z. et al., 2003, *ApJ*, 591, L17
- Tanvir N. R., Chapman R., Levan A. J., Priddey R. S., 2005, *Nature*, 438, 991

⁵ The GRB can be accompanied with a supernova explosion. For typical parameters (e.g., Mazzali et al. 2003), the supernova ejecta remain Thomson thick for $\lesssim 3$ years obscuring any early-time flaring from the magnetar but not the ($\gtrsim 100$ -year) late flares discussed here.

- Taylor G. B., Frail D. A., Berger E., Kulkarni S. R., 2004, *ApJ*, 609, L1
- Thompson C., 1994, *MNRAS*, 270, 480
- Thompson C., Duncan R. C., 1993, *ApJ*, 408, 194
- Thompson C., Duncan R. C., 1996, *ApJ*, 473, 322
- Thompson T. A., Chang P., Quataert E., 2004, *ApJ*, 611, 380
- Usov V. V., 1992, *Nature*, 357, 472
- Uzdensky D. A., MacFadyen A. I., 2007, *ApJ*, 669, 546
- van der Horst A. J. et al., 2008, *A&A*, 480, 35
- Woosley S. E., 1993, *ApJ*, 405, 273
- Zhang W., MacFadyen A., 2009, *ApJ*, 698, 1261